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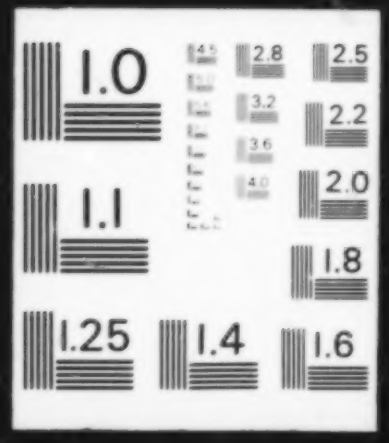

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MIXING HEIGHT DETERMINATIONS BY MEANS OF AN INSTRUMENTED AIRCRAFT

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MIXING HEIGHT DETERMINATIONS BY MEANS OF AN INSTRUMENTED AIRCRAFT

INTRODUCTION

In a general sense ambient air pollutant concentrations are a function of the rate of pollutant emission, wind speed and direction, and the altitude to which pollutants can mix. Air pollution models based at least in part on relationships such as these are being used by control agencies to develop optimum control strategies, and by the National Air Pollution Control Administration to delineate boundaries for most of the air quality control regions.[1] Information pertaining to mixing heights and wind speeds are integrated with other meteorological information in order for ESSA to furnish its forecasts of air pollution potential for the contigious United States.

The mixing layer concept has been employed by Holzworth,[2,3] who used straight forward techniques for estimating mixing heights based on regular radiosonde observations of the vertical temperature structure and subsequent surface temperature. The afternoon or daily maximum mixing height was estimated by constructing a dry adiabat from the maximum surface temperature to its intersection with the most recently observed temperature

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[1] Guidelines for the Development of Air Quality Standards and Implementation Plans, U.S. Department of Health, Education, and Welfare, National Air Pollution Control Administration, May, 1969.

[2] Holzworth, G. C., "Mixing Depths, Wind Speeds, and Air Pollution Potential for Selected Locations in the U.S." Journal of Applied Meteorology, Vol. 6, No. 6, December, 1967, pp. 1039-1044.

[3] Holzworth, G. C., "Large-Scale Weather Influences on Community Air Pollution Potential in the U.S.," Journal of the Air Pollution Control Association, Vol. 19, No. 4, April, 1969, pp. 248-254.

profile. He points out that this technique is based mainly on thermally produced turbulence, caused by the redistribution in the vertical of heat input at the ground. Since the maximum surface temperature may occur at about 1200-1600 hours local time, and since the most recent radiosonde vertical temperature measurement may have been taken 6-9 hours prior to this time, another important assumption is that the vertical temperature profile for the upper altitudes has remained reasonably constant over this period.

OBJECTIVE

This project was performed in order to evaluate mixing height estimates made by the technique employed by Holzworth and others, here designated as the Holzworth method.

METHODS

Evaluations were performed by making vertical soundings with an instrumented aircraft and recording signals that would furnish independent measures of the mixing height. Signals included a vertical temperature profile, an accelerometer trace which indicated atmospheric turbulence, and a record of particle concentrations. The mixing height was then determined on the basis of each of these parameters as illustrated in Figure 1.

Sketch 1 in this figure illustrates the Holzworth method for predicting the mixing height.

Sketch 2 illustrates the temperature profile that can be found by the instrumented aircraft during an afternoon sounding. If the temperature structure of the air mass remains constant between the time of the radiosonde and the aircraft sounding, then the two profiles should be similar. The altitude identified as the mixing height in sketch 2 is the first point above the surface at which the temperature profile becomes isothermal.

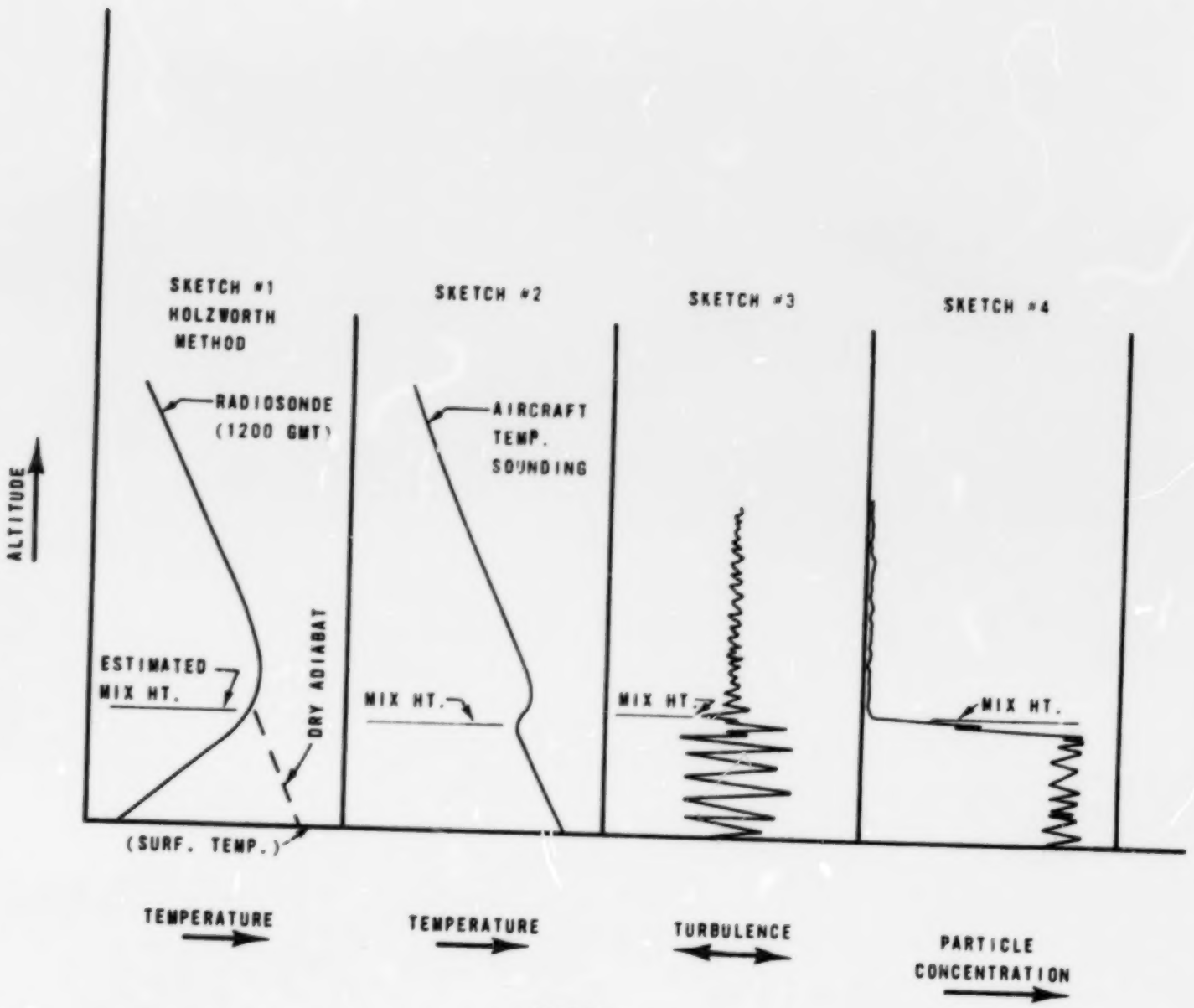

FIGURE 1

MIXING HEIGHT PARAMETERS

Sketch 3 illustrates the form in which the measures of turbulence are recorded. Signal variations represent the lateral acceleration experienced by the aircraft, and the amplitude of the trace is considered to be a measure of turbulence. In the mixing layer this was sufficient to cause lateral aircraft accelerations on the order of 0.1 g. Above the mixing layer the engine vibration produced an acceleration trace of about 0.02 g. Thus, there was found to be on the order of a five-fold difference in accelerometer amplitude below and above the mixing height. In most cases, there was found to be a rather well defined delineation between the two zones. Mixing height, as determined by this method, was the height at which the amplitude of accelerometer trace decreased to 50 percent of the mean amplitude in the mixing zone.

The size of eddy cells which produce turbulence can be implied based on the periodicity of the accelerometer trace, recorder chart speed, and aircraft speed. This and further analysis of the accelerometer readings is the subject of a thesis by Franz.[4]

Sketch 4 illustrates the concentration of suspended particulates detected below and above the mixing height. Particles greater than 0.3 μm are detected by a forward light scatter dust counter and their concentration is recorded on a strip chart. The decrease in particle concentration occurs rapidly at the mixing height if the parent air mass is clean. If the parent air mass is already laden with particles, then the decrease in particle count at the top of the mixing zone is less pronounced. The

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[4] Franz, J. J., "Aircraft Accelerometer Studies for Mixing Height Determinations," M.S. Thesis, University of Florida, June, 1970.

mixing height, as determined by this method, was the altitude at which the particle count dropped to 5 percent of full scale (50,000 particles per cubic foot or about 2 particles per cubic centimeter).

Soundings of the atmosphere were made on 33 days during the period of 8 December 1969 through 9 March 1970. On some days, repetitive soundings were made in order to follow the temporal development of the mixing height. Thus, 145 separate soundings were made For each of these aircraft soundings, Mr. Holzworth, working entirely independently, estimated the mixing height using the technique described earlier. He modified it to some extent by interpolating the temperature profile between several radiosonde locations when flights were made at intermediate locations, and when flights were between radiosonde observation times by allowing for significant temporal changes in radiosonde temperature profiles that were due to factors other than the input of heat at the ground, e.g., cold air advection, subsidence of an inversion, etc. Aircraft measurements were made when flying a steady climb to about 2000 meters depending on the terrain and mixing height, but in any event, about 300 meters above the mixing zone. Flight speeds were generally 90 mph (IAS). One crew member flew the aircraft and one operated instruments and made appropriate notation.

EQUIPMENT

A Cessna 172 (Skyhawk) aircraft was used for this activity.[5] The only aircraft modification involved the installation of a larger than normal alternator to provide the needed power for the instrument package.

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[5] McCaldin, R. O., and Johnson, L. W., "The Use of Aircraft in Air Pollution Research," J.A.P.C.A., Vol. 19, No. 6, June, 1969, pp. 405-409.

The instrument package with its several components was approved by the FAA for restricted category operation. Basically, these restrictions limited operation to daylight hours and no more than a two person crew.

As installed, the instruments were capable of measuring six parameters, although only four were used in this study. As previously indicated, the variables recorded were altitude, lateral acceleration, temperature, and aerosol concentration. Humidity and sulfur dioxide measures were available but not used.

All equipment was designed to operate on 100 volt 60 cycle current. Power was made available through two inverters operating from the aircraft 12 volt DC system. Altitude was determined by using a potentiometric absolute pressure transducer acting in a voltage divider network. Excitation was provided by a regulated power supply. The output from the transducer was fed directly to the null-balance potentiometric recorder. An adjustable zero was provided on this channel of the recorder to accomodate barometric pressure changes, and adjustments were made at the beginning of each flight.

Temperature was measured with a linear thermistor situated in one or the other of two parallel DC bridge curcuits, providing overlapping temperature ranges. These circuits proved reliable, but did suffer from component temperature sensitivity. The error due to this problem became more acute at very low ambient temperatures. Response time of this element was on the order of five seconds or less.

Turbulence was sensed by a potentiometric type yaw accelerometer rigidly fixed to the airframe. The total range of this instrument is $\pm$ 0.33 g. Its excitation was through a regulated DC power supply and the output fed directly to the null-balance potentiometric recorder.

Aerosol concentrations were sensed with a Bausch and Lomb 40-1 dust counter which is of the forward light scatter type. For most

measurements of mixing height, aerosols 0.3μm and larger were counted. The instrument has other size range selections at the discretion of the user. The output of this device is normally logarithmic. A log-linear attachment available from the manufacturer provided a linear conditioned signal directly compatible with the null-balance recorder. Response time of this instrument as installed in the aircraft has been measured just under two seconds.

As indicated, all variables are routed to a null-balance potentiometric recorder. This unit has four channels, thereby allowing all variables to be simultaneously recorded on a single chart. Chart speed for this work was standardized at one inch per minute.

FINDINGS

1. Comparison of ESSA and Aircraft Temperature Profiles

The first step was to see how closely the aircraft temperature soundings compared with those measured by the ESSA radiosonde. Table 1 shows the date, location, and times for which nearly comparable measurements were taken. The differences between the radiosonde temperature and that recorded from the aircraft at the surface and at 1000 meters are shown. The temperatures, as measured by the aircraft, averaged almost $2^{o}C$ lower than those measured by radiosonde. It should be noted that the morning flight soundings had to be made approximately one to three hours later than the radiosonde observations, due to an FAA flight restriction which limited the aircraft operation to daylight hours. More important than the absolute difference in values is the ability of both techniques to disclose similar vertical temperature profiles. This is because the mixing height based on aircraft temperatures is defined as the altitude at which the temperature lapse rate first becomes iso-

TABLE 1

COMPARISON OF RADIOSONDE AND AIRCRAFT
VERTICAL TEMPERATURE PROFILES

Location	Date	Hour		TEMP DIFFERENCE Radiosonde-Aircraft (^{o}C)	
		Radiosonde	Aircraft	Surface	1000m
Tampa, Fla.	18 Dec 69	0618	0706	1.0	-1.0
Waycross, Ga.	7 Jan 70	1800	1750	1.2	2.1
			1810	2.6	2.5
Waycross, Ga.	8 Jan 70	0615	0725	5.5	5.0
			0740	-	5.0
Tampa, Fla.	22 Jan 70	0638	0715	2.7	1.1
			0755	2.2	1.7
Waycross, Ga.	13 Feb 70	1817	1527	-1.0	1.0
			1642	-1.3	0.5
Grand Junction Colo.	7 Mar 70	0417	0715	2.5	-1.2

thermal, and is not dependent on the absolute temperature itself. The similarity of radiosonde and aircraft temperature profiles is shown in Figure 2. From these data it was concluded that aircraft temperature profiles were a true reflection of those obtained by radiosonde.

2. Comparison of Estimated and Measured Mixing Heights

A correlation matrix was developed for the mixing heights as determined by the Holzworth method, and as compared with that determined from vertical temperature structure found by the aircraft; that determined from aircraft turbulence; and that determined by particle concentration.

Figures 3, 4, 5, and 6 show the correlation diagrams when these various techniques are compared, and Table 3 contains the correlation statistics for these comparisons.

The sample size in these comparisons varied from 108 to 121 out of a total of 145 soundings. Differences are due to a combination of factors including instrument malfunctions resulting in missing data and several late afternoon flights for which the technique employed by Holzworth is not applicable, e.g., after the afternoon surface temperature has begun to cool.

These data suggest that the mean mixing height estimated by the Holzworth method is not significantly different from that measured by aircraft turbulence. The Holzworth method and the aircraft turbulence technique both give a mean mixing height seven to nine percent greater than that found by the aircraft temperature profile. The smaller mixing height based on aircraft temperature profiles is probably due to the significance of the isothermal point identified as the mixing height. From examination of a number of the original strip charts it appears that due to momentum parcels of air may continue to rise for several hundred feet above the point at which their density and temperature

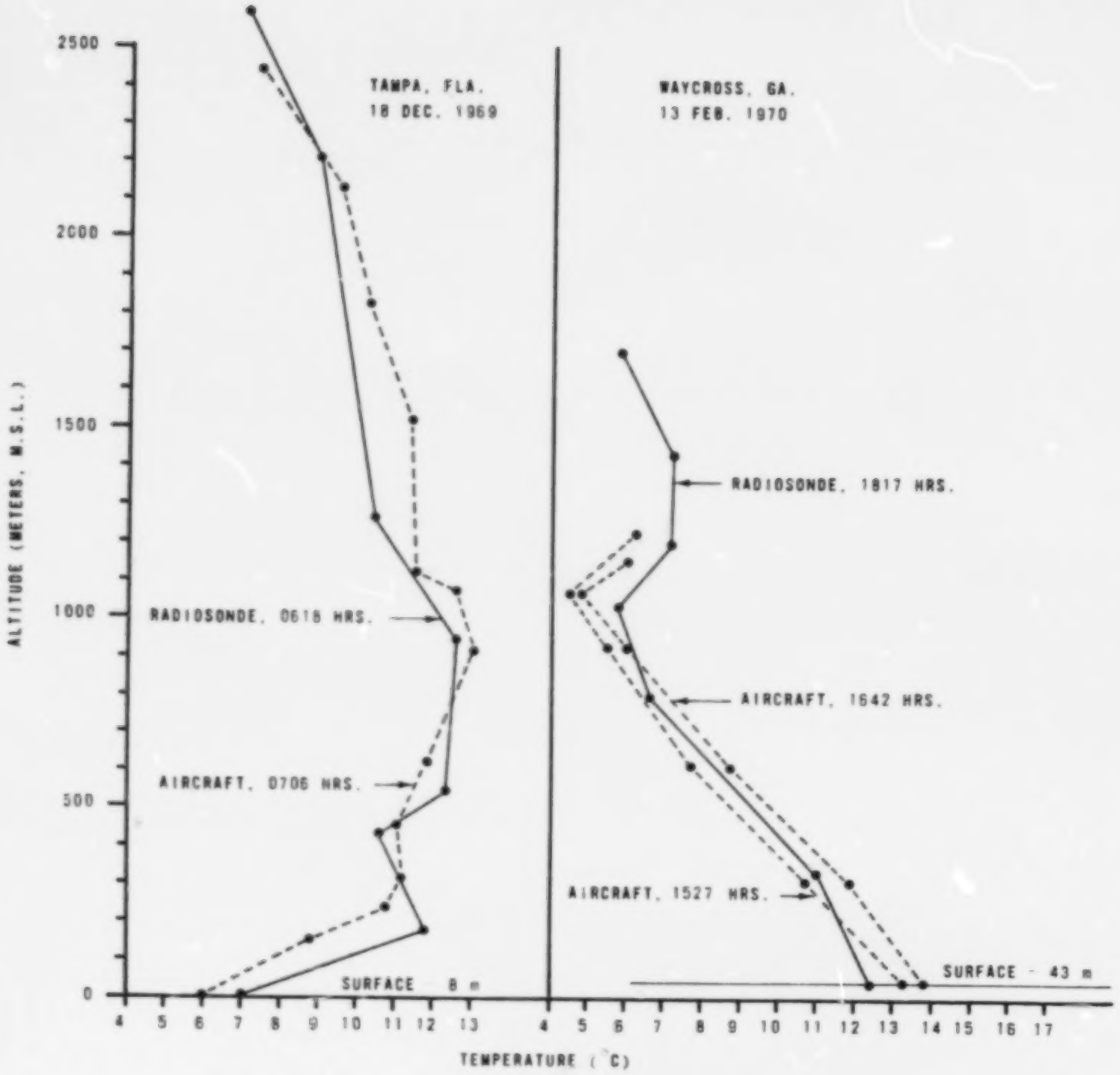
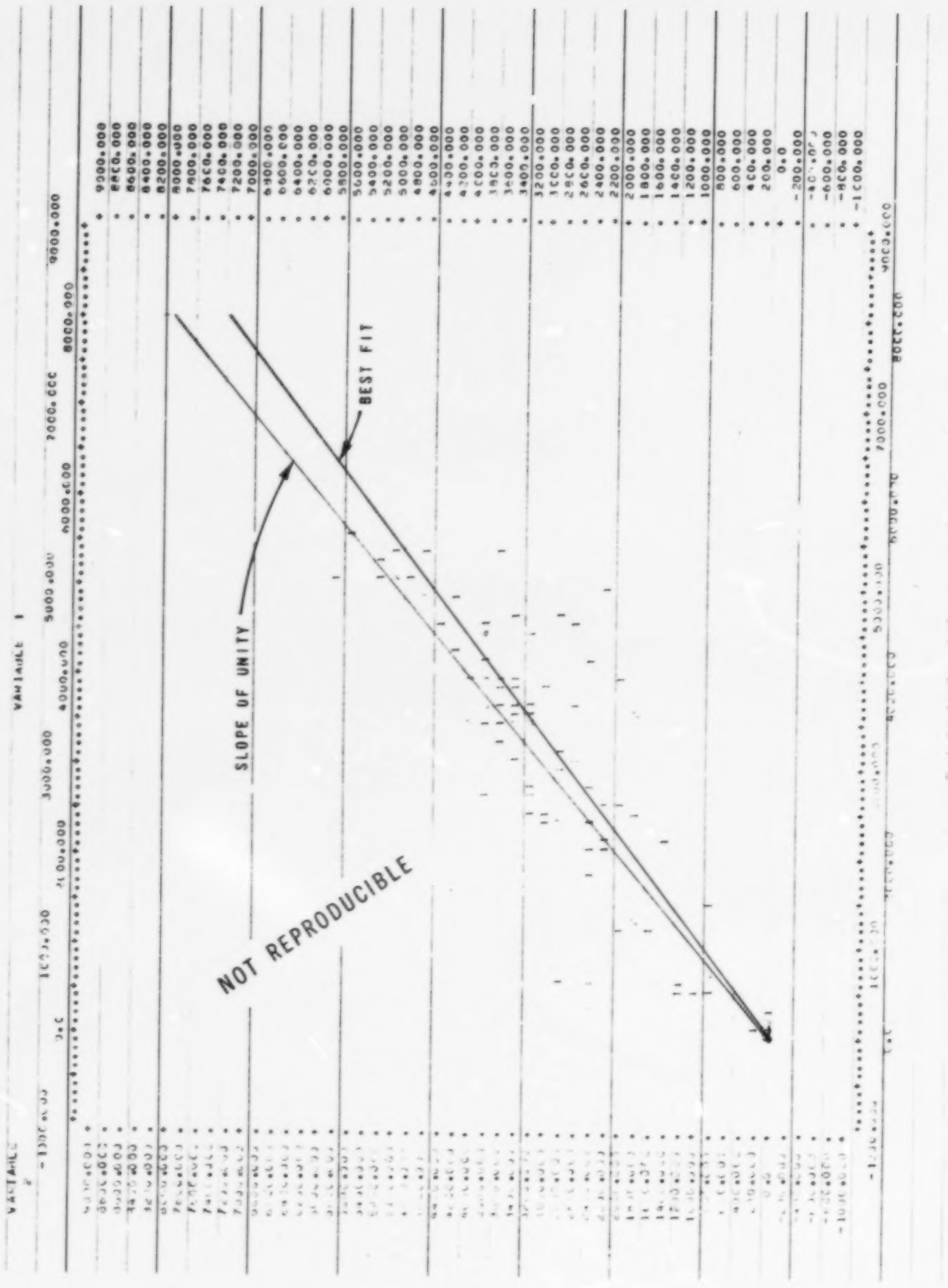


FIGURE 2

COMPARISON OF RADIOSONDE AND AIRCRAFT
VERTICAL TEMPERATURE PROFILES



MIXING HEIGHT DETERMINED BY HOLZWORTH (FEET)

FIGURE 3

MIXING HEIGHT REGRESSION: HOLZWORTH TECHNIQUE VS. AIRCRAFT TEMPERATURE

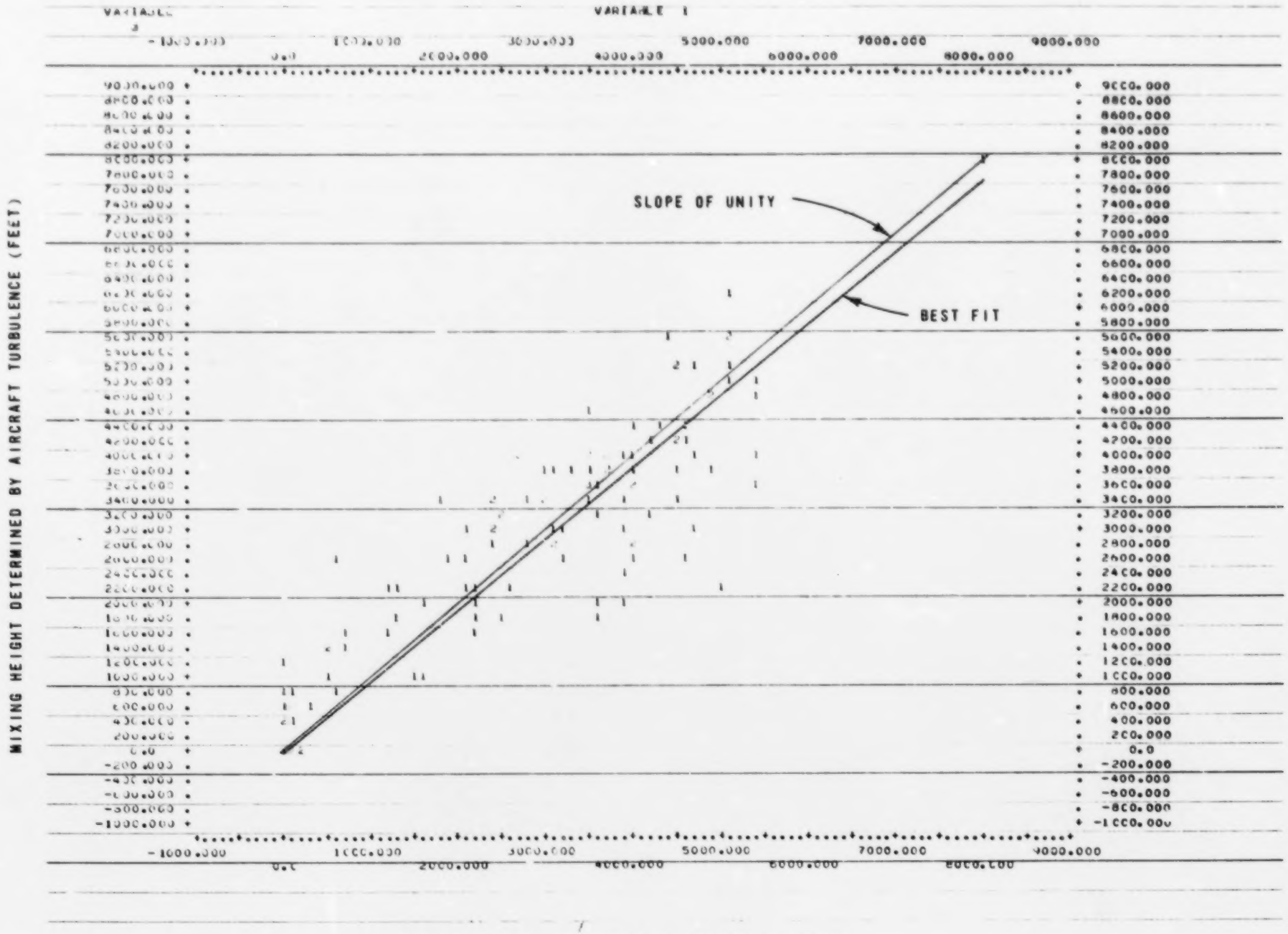


FIGURE 4

MIXING hEIGHT REGRESSION: HOLZWORTH TECHNIQUE VS. AIRCRAFT TURBULENCE

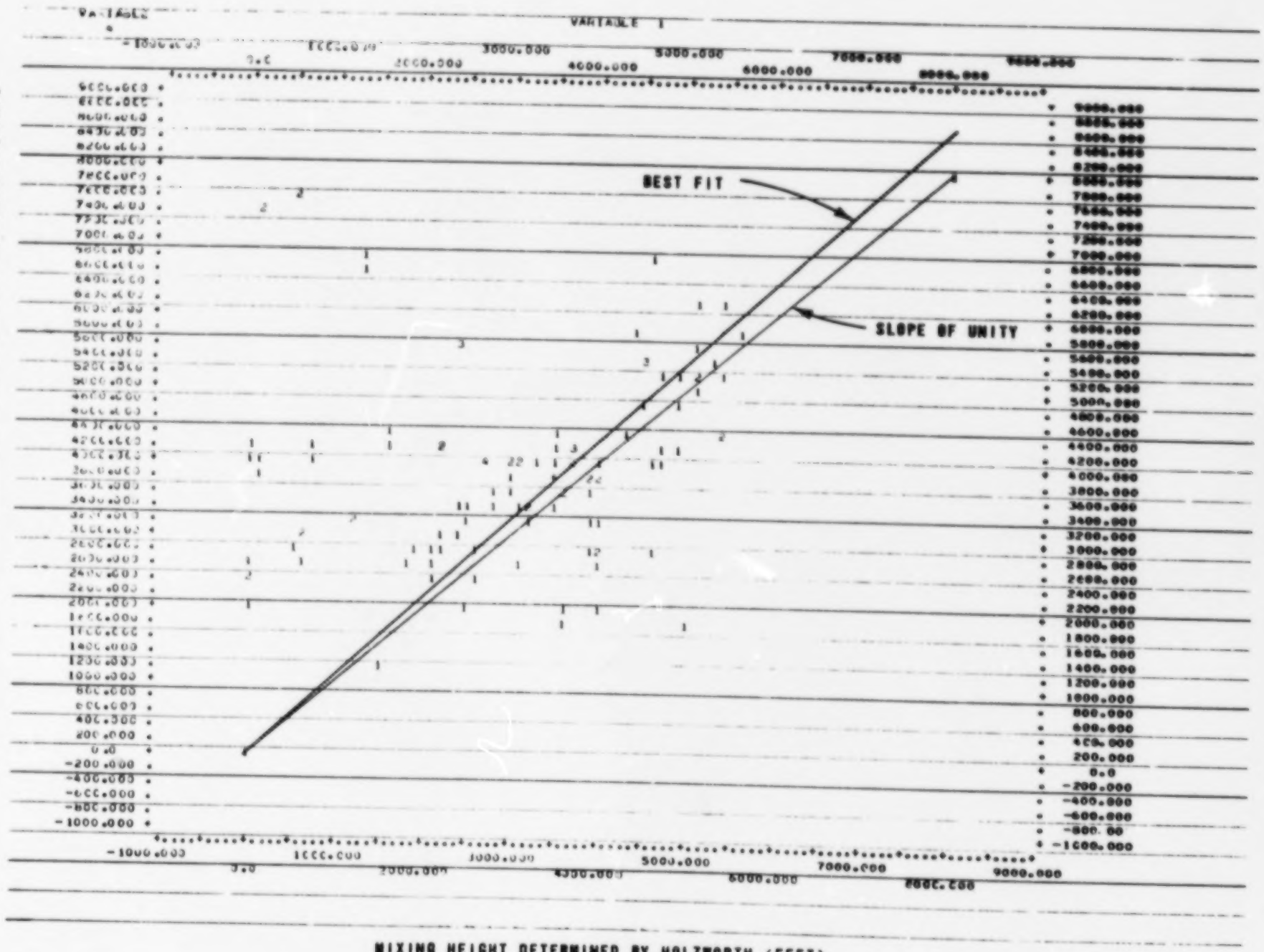

VARIABLE 1
VARIABLE 2
BEST FIT
SLOPE OF UNITY
MIXING HEIGHT DETERMINED BY CONCENTRATION OF SUSPENDED PARTICULATES (FEET)
MIXING HEIGHT DETERMINED BY HOLZWORTH (FEET)

FIGURE 5

MIXING HEIGHT REGRESSION: HOLZWORTH TECHNIQUE VS. PARTICLE CONCENTRATION

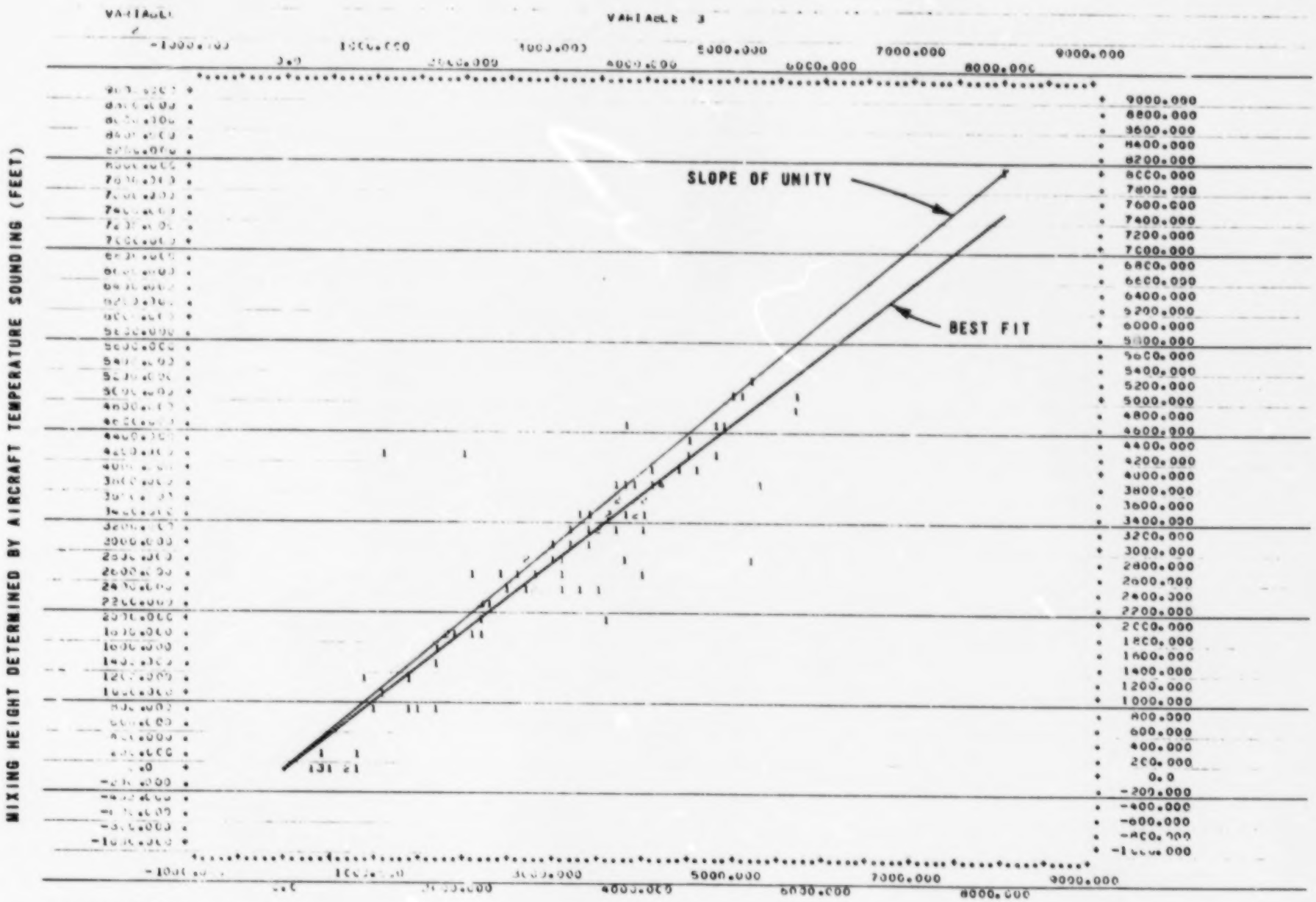

SLOPE OF UNITY
BEST FIT
MIXING HEIGHT DETERMINED BY AIRCRAFT TEMPERATURE SOUNDING (FEET)
MIXING HEIGHT DETERMINED BY AIRCRAFT TURBULENCE (FEET)

FIGURE 6

MIXING HEIGHT REGRESSION: AIRCRAFT TEMPERATURE VS. AIRCRAFT TURBULENCE

TABLE 3

CORRELATION OF VARIOUS MEASURES OF THE MIXING HEIGHT

Comparison	Sample Size	Correlation Coefficient	Slope of Line of Best Fit	Significance of Difference in Slope of Line of Best Fit and Slope of Line of Unity at 95 Percent Confidence Level
Holzworth estimated height vs. aircraft temperature height	113	0.87	0.91	Yes
Holzworth estimated height vs. aircraft turbulence height	117	0.87	0.97	No
Holzworth estimated height vs. aircraft particle concentration height	121	0.25	1.08	No
Aircraft turbulence height vs. aircraft temperature height	108	0.93	0.93	Yes

reach equilibrium with their environment. The amount of additional rise appears to depend upon the stability of the environment air. As these parcels rise beyond their equilibrium point they continue to cool adiabatically. Subsequent mixing with the environment air produces a stable layer such as an inversion. Although Holzworth's estimates do not allow for this effect, it is compensated to some extent by his neglect of shallow superadiabatic layers next to the ground.

The mixing height predicted by the Holzworth technique is also not significantly different from that determined by the height to which aerosols have mixed. It should be pointed out, however, that the correlation coefficient for this comparison is only 0.25. This wide scatter of data points can be best explained by considering the history of the air mass in question. If mixing occurs in a clean air mass, then aerosols will be distributed to the top of the mixing layer. In the evening the mixing activity diminishes, but the aerosols remain aloft. Although the particles are influenced by gravity, their settling rate is slow. For example, a one μm diameter particle of unit density would settle about three meters over a 24-hour period. Thus, on the second day small aerosols would remain mixed in the air mass nearly to the height of the mixing layer of the prior day. If mixing heights were determined the second or any subsequent day in the air mass, the particle distribution would be an indicator only of the greatest height the mixing layer had achieved, and not necessarily the height of the mixing layer at the time of measurement.

DISCUSSION

Since these aircraft techniques of temperature, turbulence, and aerosol measurements for determination of mixing heights are not common,

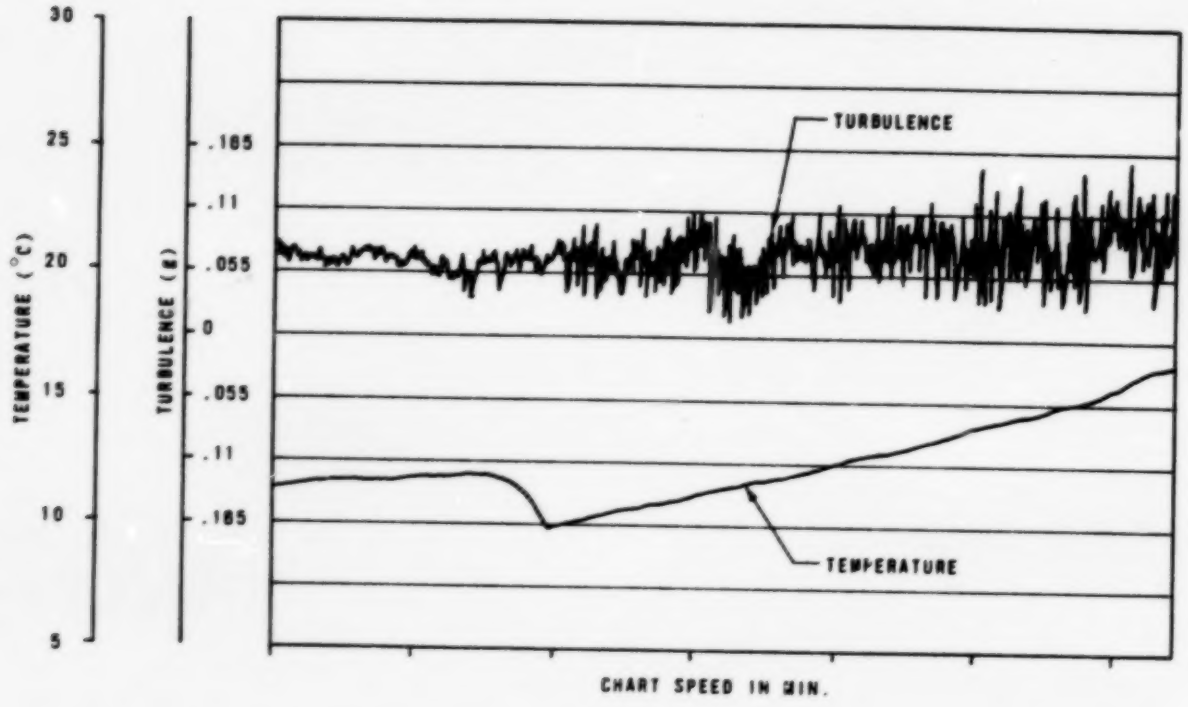
several portions of the original strip chart data are presented and discussed for illustrative purposes.

Figure 7 shows measurements made during a climb over Waco, Texas. The chart reads from right to left, and the aircraft altitude can be read from the solid line starting at the lower right hand corner of the figure. Aerosol concentrations are also recorded on the bottom portion of the figure. This shows a gradually decreasing concentration of aerosols until the mixing height is reached. At that time there was a very rapid decrease in aerosol concentration. Appropriate scale units are shown on the left margin. The turbulence scale shows amplitude only, and the zero reference was arbitrarily placed on the chart.

On the top portion of the figure the steady line represents the temperature associated with altitude. It decreased rather steadily with altitude until 2400 feet was reached. Above this altitude a marked inversion occurred as shown by the $2^{o}C$ increase in temperature. Aircraft turbulence is shown by the fluctuating trace at the top of the figure. The amplitude of fluctuation decreased as the aircraft climbed above the mixing layer. The smaller acceleration traces above the mixing layer represents aircraft vibration and response to movement of aircraft flight controls.

Using the criteria for measurement which were described earlier, mixing heights at Waco were as follows:

Method	Altitude (ft) M.S.L.
Holzworth Estimate	3000
Aircraft Temperature	2400
Turbulence	2300
Aerosols	2500



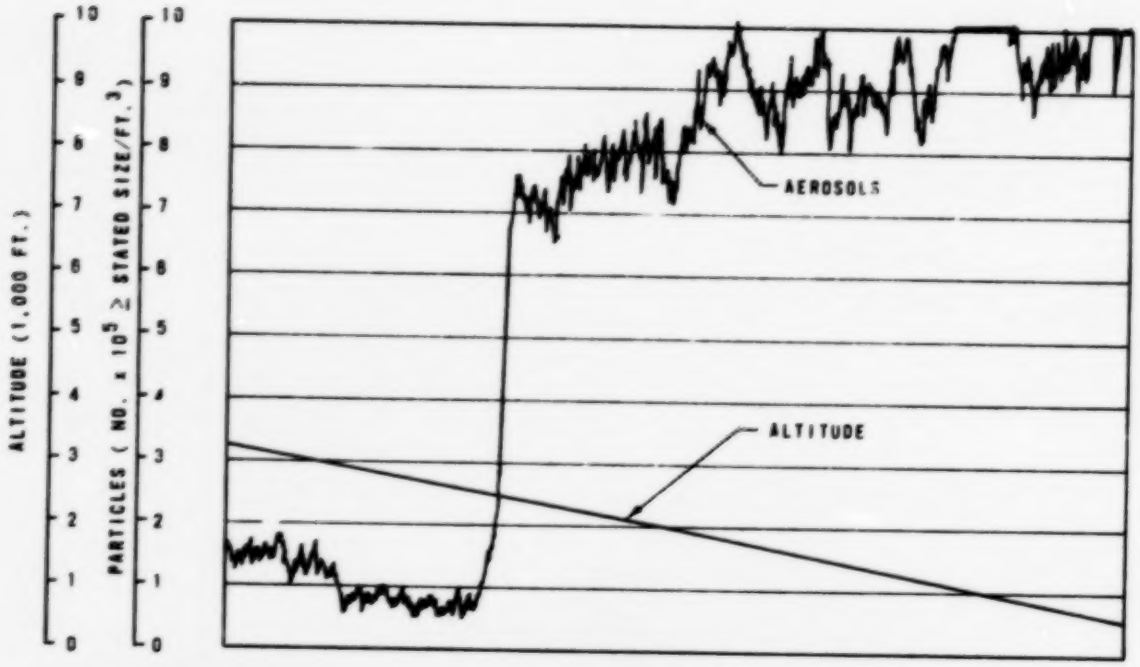


FIGURE 7
MIXING HEIGHT DETERMINATIONS
WACO, TEXAS 4 MARCH 1970 1400 HOURS

Figure 8 illustrates the influence that aerosol concentrations below the mixing layer have on visibility. This is a composite photograph taken near Waco about a minute after the aircraft climbed above the mixing layer. One view faces the sun, and the other is with the sun behind the camera. The effects of visibility reduction on flying safety can be illustrated by referring to a fatal mid-air collision between a North Central airlines Convair 580 and a Cessna 150 near Milwaukee on August 4, 1968. The National Transportation Safety Board report said in part the probable cause of the collision was "... the inability of the Convair flight crew to detect the Cessna visually in sufficient time to take evasive action, despite having been provided with three radar traffic advisories concerning the latter aircraft." There were no clouds obstructing visibility, but flight visibility was reduced to about three to five miles due to smoke, haze, and sun glare. In addition there were insect smears on the Convair windshield - a fatal combination.

Figure 9 illustrates an anomoly between measurements. The mixing height by Holzworth's method was estimated to be 2250 feet. Based on the first isothermal point the mixing height was measured at 1700 feet; based on turbulence at 1900 feet. However, based on aerosols it was measured at 4500 feet, and this suggests that aerosols had been moved aloft at a prior time, and thus were independent of mixing during the day in question.

Figure 10 illustrates developments in the mixing height during the course of a day as well as some of the unexpected findings. At 0810 there was a strong inversion and good agreement between various mixing height measurements. By 1115 the inversion was not so pronounced. There was good agreement between the temperature and turbulence height measurements. However, there was additional turbulence further aloft, and particle concentration decreased only slowly with height. By 1500 the

NOT REPRODUCIBLE

BACK TO SUN

FACING SUN

FIGURE 8
MIXING LAYER
WACO, TEXAS 4 MARCH 1970 1400 HOURS

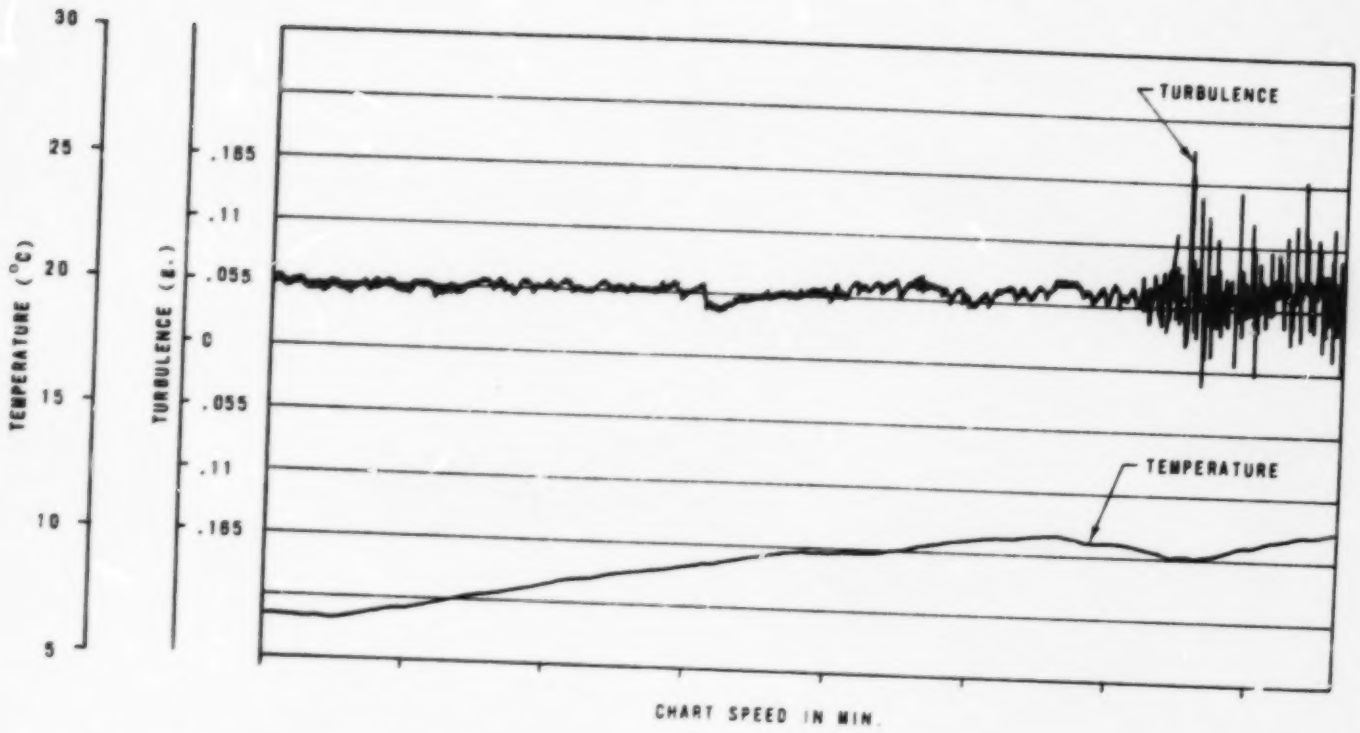


FIGURE 9
MIXING HEIGHT DETERMINATION - SHOWING DISPARITY BETWEEN MEASUREMENTS
GAINESVILLE, FLORIDA 15 DECEMBER 1969 1125 HOURS

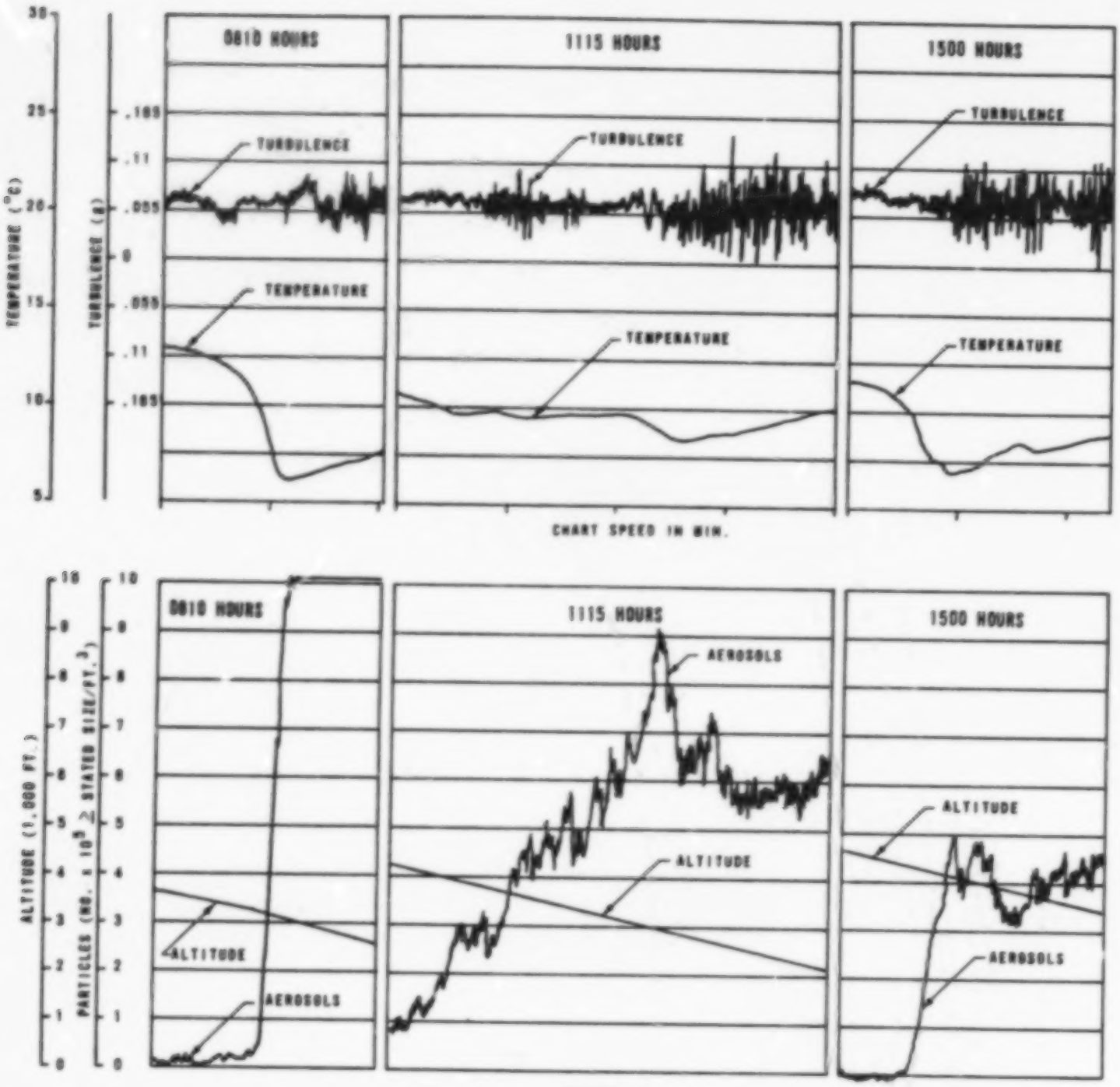


FIGURE 10

MIXING HEIGHT DETERMINATION SHOWING DEVELOPMENT DURING DAY
GAINESVILLE, FLORIDA 18 FEB. 1970
0810, 1115, 1500 HOURS

temperature profile suggested a double inversion. In accordance with the selection criteria, the first isothermal above the ground was chosen as the mixing height. On the basis of comparison with turbulence and aerosol data it appears quite likely that the second and larger inversion actually established the mixing height.

Figures 11, 12, and 13 all pertain to measurements made over Gainesville, Florida on 16 December 1969. The series of figures are presented to show how the mixing height developed during the day and to illustrate the temperature and turbulence patterns.

Figure 11 shows the vertical temperature structure at approximately two-hour intervals during the day. Notice the cooling that occurs with time at the top of the mixing layer, e.g., in the 250-650 meter layer from 0805 to 1010, as discussed on pages 9 and 16.

Figure 12 shows the mixing heights as determined by each technique. The vertical scale is compressed in order to permit visual comparison with the temperature profiles in Figure 11.

Figure 13 shows the accelerometer trace for each sounding. The height of the mixing layer is noted for each trace, but the vertical scale between traces is not identical. This is because their length is a function of aircraft climb rate which varied somewhat between the several flights. Perhaps the most interesting feature of these traces is the accelerometer amplitude pattern. Amplitude is greatest around mid-day and suggests that the most vigorous turbulence occurred at that time. The mixing height increased until about 1605 hours, but by that time the accelerometer amplitude had diminished rather uniformly through its height. Then by 1730 it had collapsed in its entirety. The relationship between heat input, temperature lapse rates, and amplitude of turbulence is to be the subject of a later inquiry.

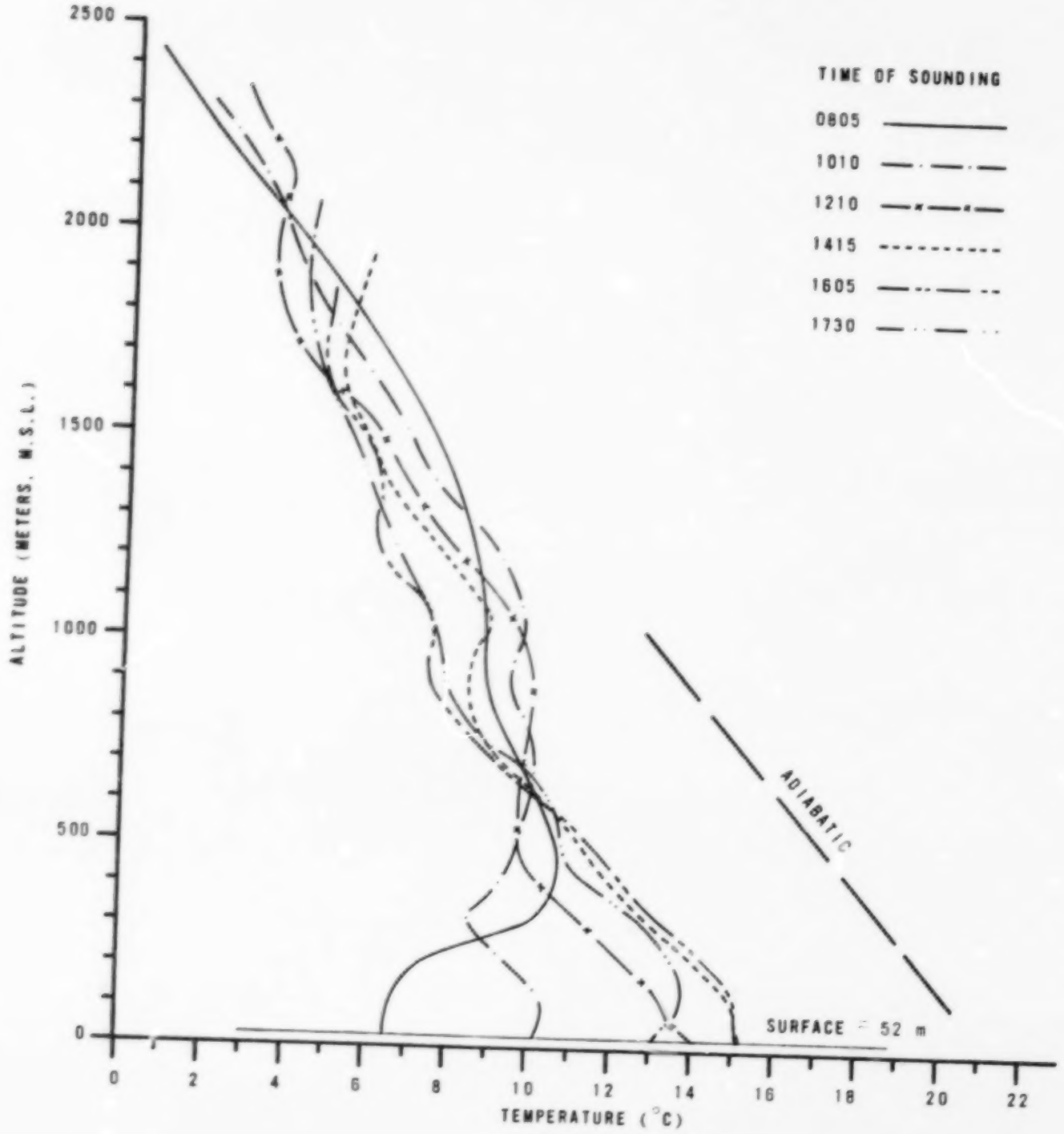


FIGURE 11

VERTICAL TEMP. STRUCTURE
GAINESVILLE, FLORIDA 16 DEC. 1969

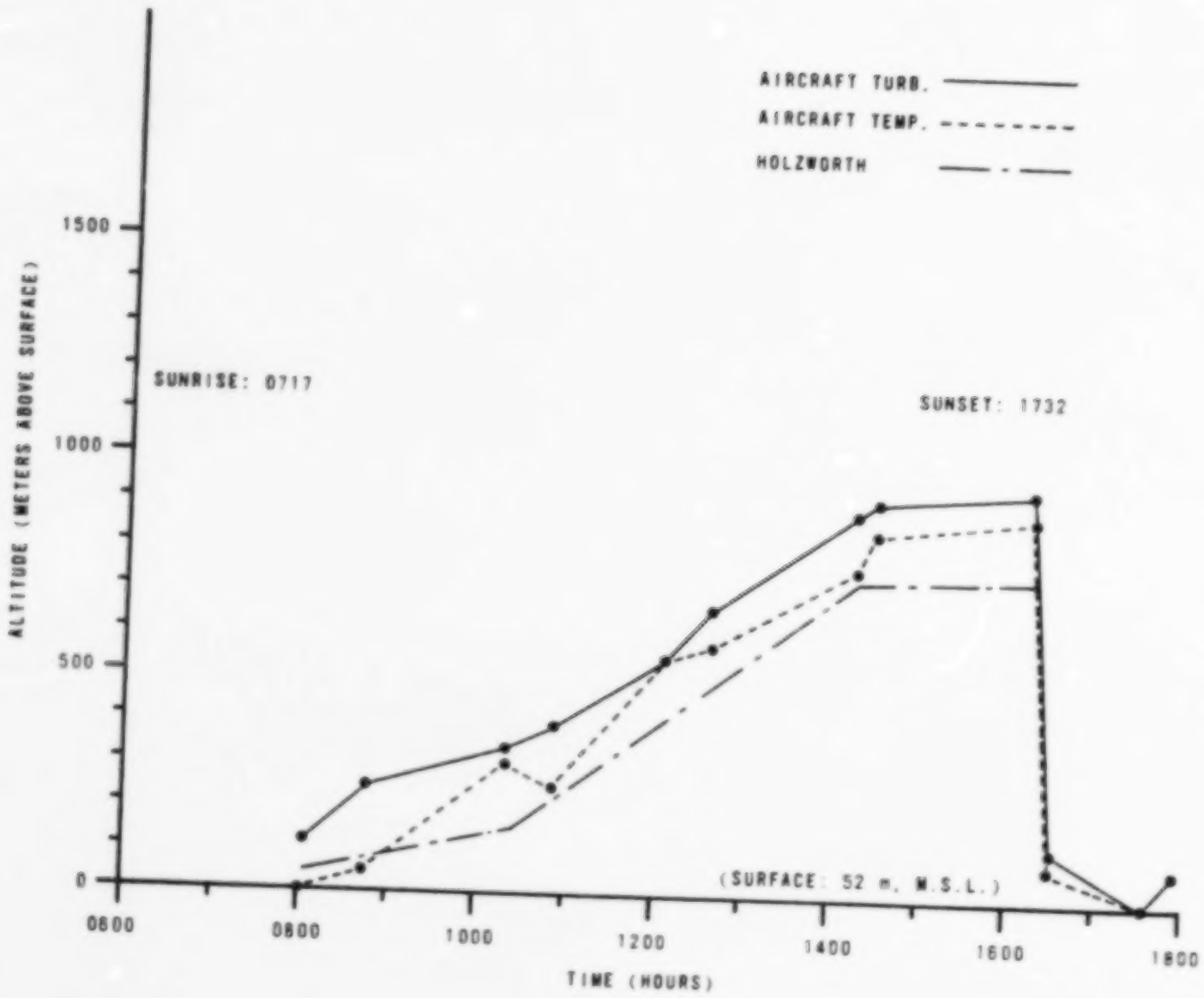


FIGURE 12

DEVELOPMENT IN MIXING HEIGHT DURING COURSE OF DAY -
AS DETERMINED BY SEVERAL METHODS.
GAINESVILLE, FLA. 10 DEC. 1970

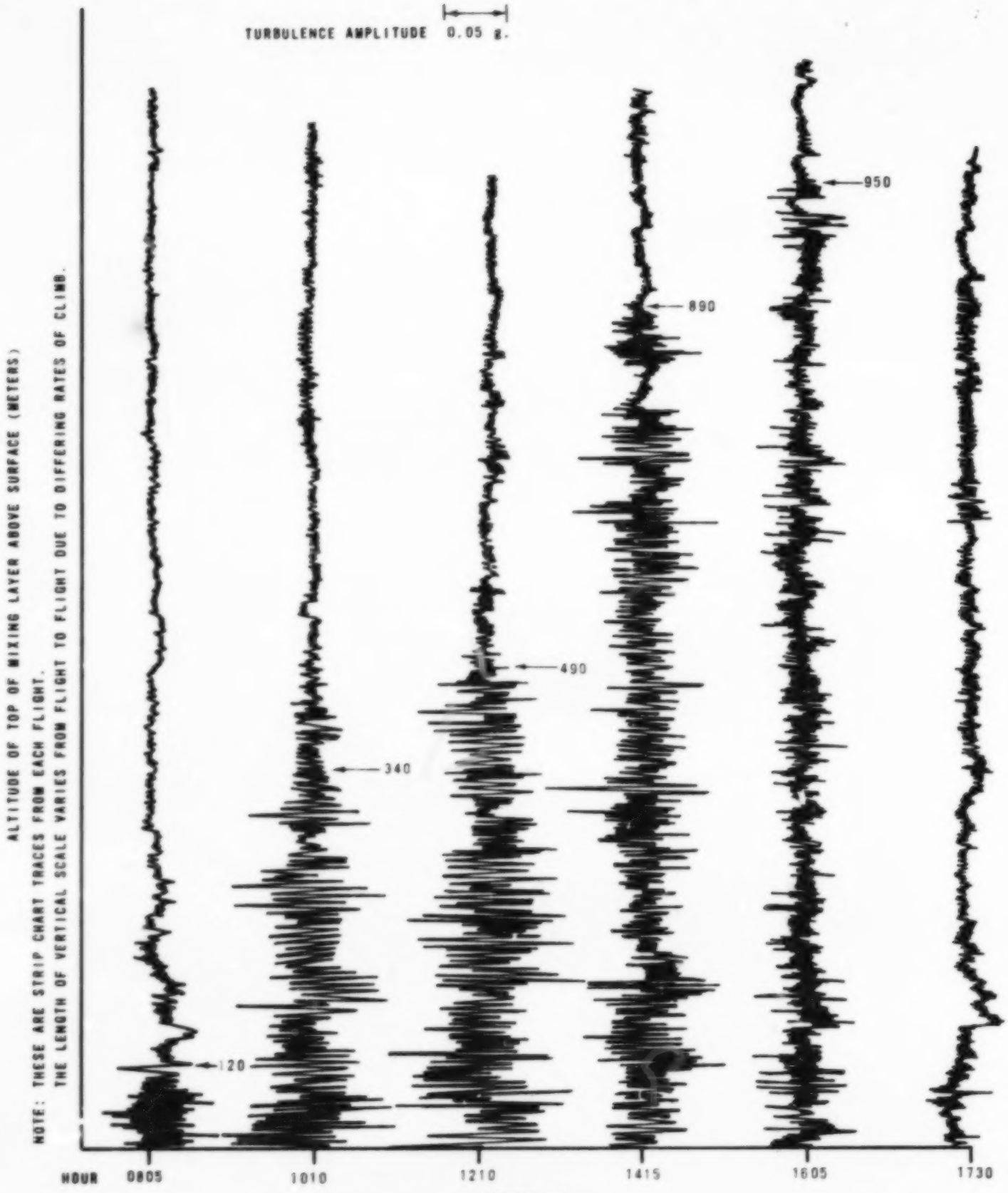


FIGURE 13

DEVELOPMENT OF MIXING HEIGHT AND AMPLITUDE OF TURBULENCE -
AS DETERMINED BY AIRCRAFT ACCELEROMETER.
GAINESVILLE, FLA. 16 DEC. 1969

Figure 14 shows the mixing height measurement made in New Orleans on 9 March 1970. It also shows the influence of Lake Ponchartrain on turbulence and the contribution of background aerosol concentrations to New Orleans pollution levels.

Lake Ponchartrain is immediately north of New Orleans, and when these observations were made, winds were from the north across the lake and into the city. The flight was started at Lake Front Airport on the edge of Lake Ponchartrain, and the initial climb was made to the north over the lake. Then a turn was made to the south and the flight continued over the shoreline and over an industrial area of town.

The accelerometer trace shows turbulence on the take off roll over the hot concrete runway. Lack of turbulence can be noted during the climbing turn over the lake. Then turbulence was picked up again shortly after passing southward over the shoreline.

During the flight over the lake, the aerosol concentration was approximately 3×10^5 particles $\geq 0.3\mu m$ per cubic foot (10 per cm^3). Then shortly after returning over the land mass, the aerosol concentration gradually increased to a rather uniform level of 8 to 9×10^5 particles per cubic foot (30 per cm^3) until the top of the mixing layer was reached.

These data suggest that about one-third of the total number of particles in New Orleans originated upwind of that city. This is only true on a count basis, since emission of relatively larger particles from sources in New Orleans could markedly affect a weight determination.

These small particles can affect visibility, and Figure 15 shows the contrast in visibility above and below the mixing layer. This photo was taken just as the aircraft passed through the top of the mixing layer, and the irregularities at the interface of the two zones can be seen.

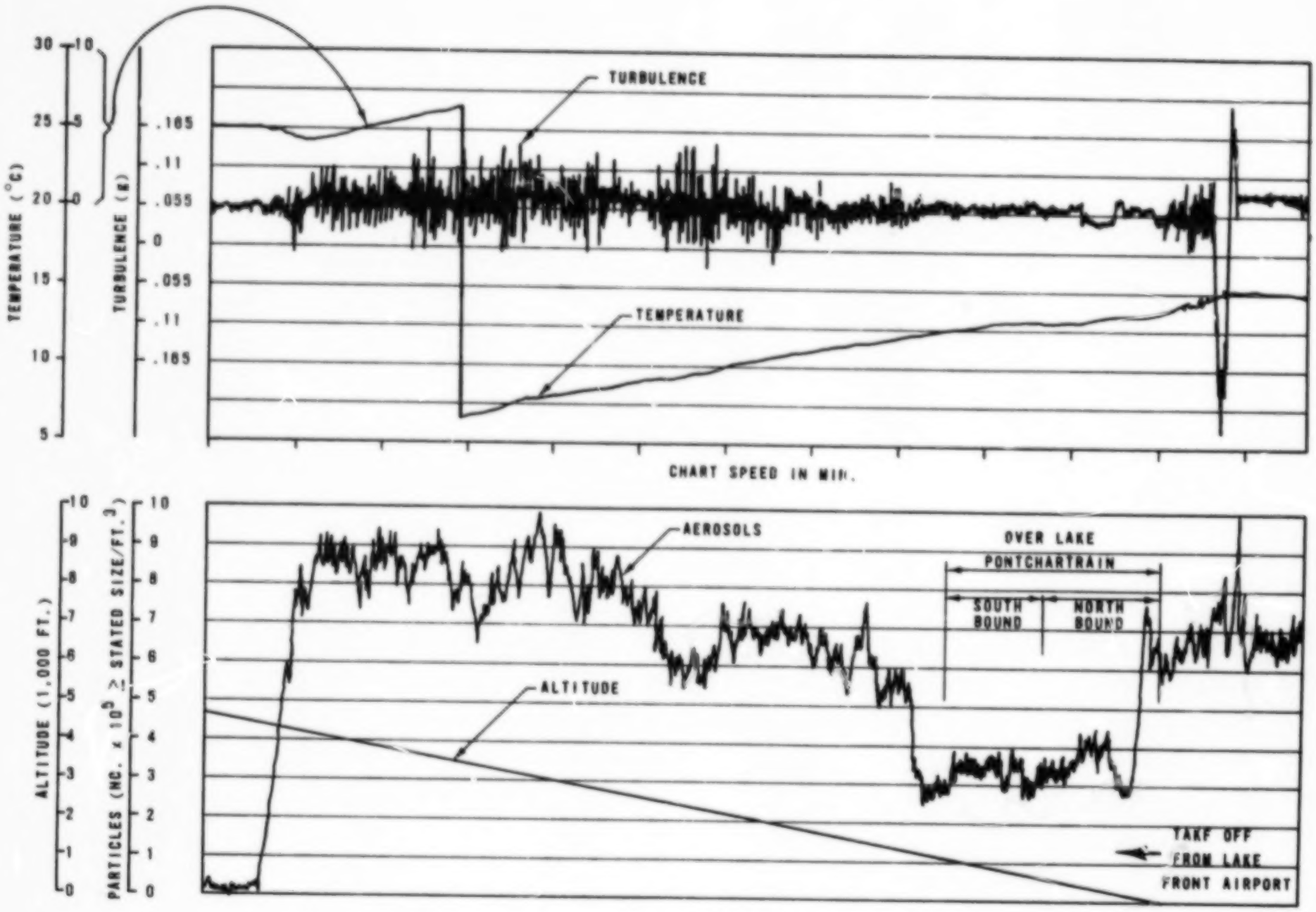
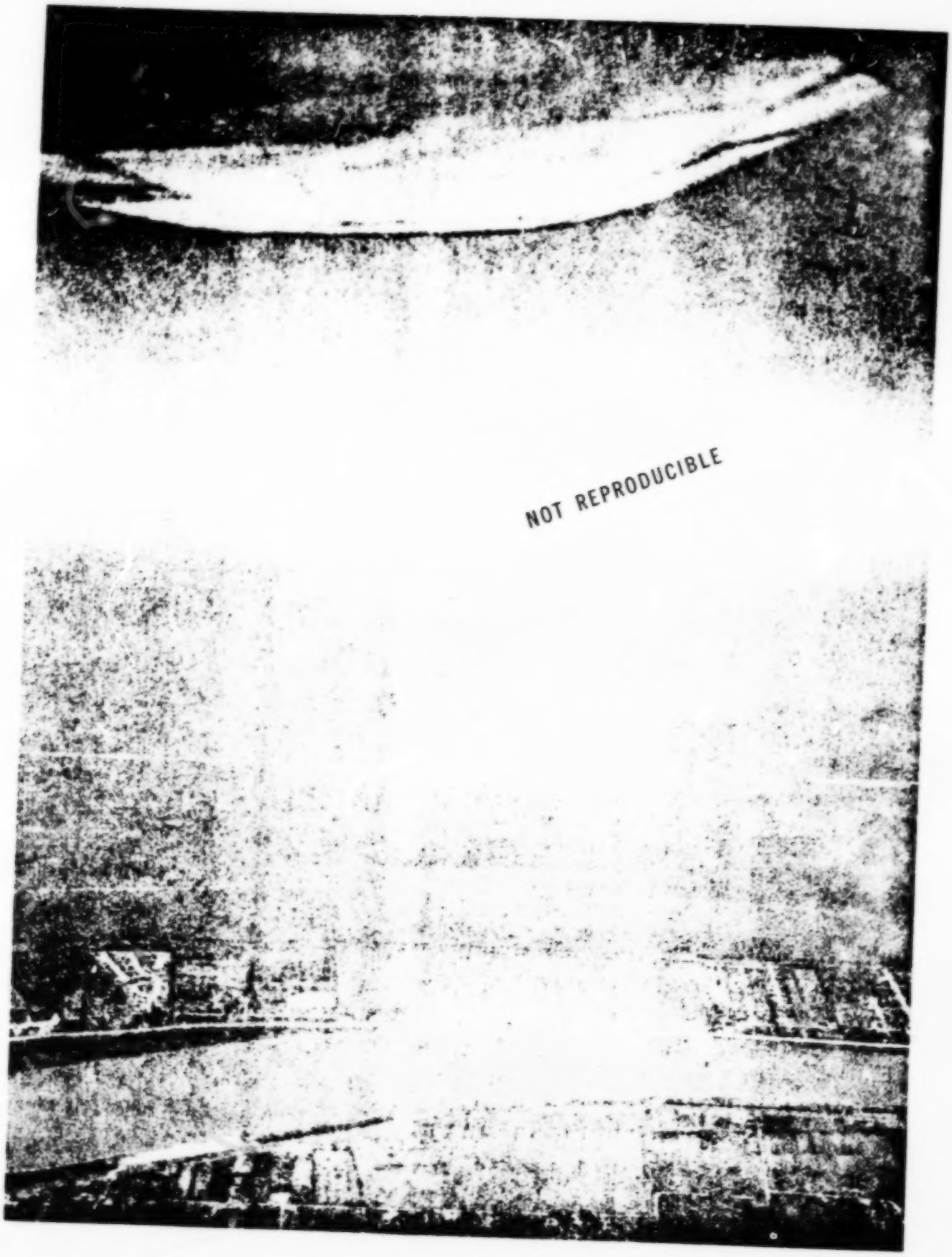


FIGURE 14

INFLUENCE OF LAKE PONTCHARTRAIN ON TURBULENCE AND AEROSOL ABUNDANCE.
NEW ORLEANS, LOUISIANA. 9 MARCH 1970. 1220 HOURS.



NOT REPRODUCIBLE

FIGURE 15
MIXING LAYER
NEW ORLEANS, LA. 9 MARCH 1970, 1220 HOURS

SUMMARY AND CONCLUSIONS

A series of measurements were made to evaluate the Holzworth method used by ESSA for calculating mixing heights. One hundred forty-five atmospheric soundings were made in an instrumented aircraft to determine the vertical temperature structure, atmospheric turbulence as indicated by an accelerometer, and height to which pollutants were mixed as determined by aerosol concentrations.

Mixing height measures based on each of these techniques were then compared with estimated mixing heights based on Holzworth's method. It was found that there was no statistical difference between the Holzworth estimates and aircraft turbulence measures of the mixing height. Mixing heights based on aircraft temperature profiles were found to be 7 to 9 percent smaller than the Holzworth and aircraft turbulence techniques. This is thought to be due to the criteria used to select mixing heights from the aircraft temperature profiles.

There was no statistical difference between mixing heights based on Holzworth's technique and aerosol distribution. However, only a poor correlation ($r = 0.25$) was found, probably due to detection of aerosols which had been moved aloft on previous days.

Marked differences in visibility below and above the mixing layer were photographed, and particle concentrations in each atmospheric regime were recorded. In New Orleans for example, there were about fifty times more particles in the mixing layer than found in the clean air above.